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Oil Management Solutions for Manifolding Scroll Compressors for Refrigeration Systems

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ABSTRACT

Manifolded compressors are widely used in existing refrigeration systems such as cold rooms, display windows and ice machines. Scroll compressors are increasingly used in refrigeration systems, hence manifolded scroll compressors are easily found in the current market. The manifolding of two, three or even four compressors provides many benefits. It can provide capacity modulation; it can offer lower starting load of the system; it also enables the change of one compressor when it is tripped without shutting down the whole system. The key success factor of design of the manifold is to ensure the right balance of the oil between compressors in different running conditions. It is vital for the compressor to maintain the proper level and quantity of oil for its reliability. Two kinds of oil management solutions are predominant. One is the active solution which includes a mechanical or electronic oil level control device (oil level regulator) to control the oil feeding in order to maintain the oil level inside of the compressor crankcase. This solution is maturely used in the market. The other is the passive solution which relies on the piping design to achieve a good oil balance. The passive one is more interesting for its cost effectiveness and robustness due to fewer components, however, it is more difficult to handle. In this paper, three different passive oil management solutions for even tandem systems are studied. The first solution is that each compressor has its own respective oil separator; oil separated in the oil separator is returned back to the corresponding compressor crankcase, and the oil balance line is installed to avoid that one compressor oil level is much higher than the other if OS(oil separator) efficiency is different or any OS is blocked. The second solution consists of two compressors sharing one common oil separator; oil separated from the OS is fed back to the common suction line, and is then led back to each compressor with refrigerant gas. The oil return has to be split equally between the running compressors; the oil state could be as spray with the gas and as droplets along the length and bend of the piping. Since the oil is returning back together with the suction gas, gas balance is critical and gas velocity in the suction line is very important. Suction header and suction branch design is described in detail in the paper to ensure the gas balance and oil return. The oil balance line is installed between two compressors in order to balance the oil level. The third solution is that two compressors share one oil separator; oil is returned back to one compressor crankcase and then through the oil balance line to feed another compressor's crankcase. All of the above three passive solutions are working but have their own advantages and disadvantages. Test results for each solution are shown in the paper. Also, the vibration analysis and the tests are described to optimize the piping design for good acoustic result.

1. INTRODUCTION

Manifolded compressors are widely used in existing refrigeration systems such as cold rooms, display windows and ice machines. Scroll compressors are increasingly used in refrigeration systems due to their high efficiency, low sound level, and lower vibration. Currently, manifolded scroll compressors are easily found in the air-conditioning market. The manifolding of two, three or even four compressors provides many benefits. It can provide a primary capacity modulation to fit the cooling requirement which reduces system power consumption and results in better seasonal efficiency. Also it can offer lower starting load of the system compared with using one big compressor. And finally it enables the change of one compressor when it is tripped without shutting down the whole system (Yan, 2007; Zhang, 2011). Lubricating oil is very important for scroll compressor reliability. First, the oil film ensures a proper work of thrust bearing as well as reduces wear out of other friction couples; second, it creates a seal between the orbiting scroll and fixed scroll to prevent gas leakage between compression pockets with different pressure; third, it cools the compressor motor as well as dampens vibration and reduces acoustic noise. Therefore, it is vital to maintain the proper oil level and quantity inside a compressor. When using manifolding systems, the compressors may not start/stop simultaneously, and the running time of each compressor may not be the same, also the refrigerant velocity inside the pipework varies with different numbers of compressors running; all of the factors will cause different oil return. Therefore, the oil return and oil balancing are the key factors for design of manifolding compressor systems (Cheng, 2011; Shan, 2007; Yin, 2012). In refrigeration systems, oil return is more difficult due to low evaporating temperature and long pipework between evaporators and condensing units. Therefore, an oil separator (OS) and an oil level regulator (OLR) are usually installed in these systems. Oil level control uses mechanical or electronic equipment to detect the compressor oil level and controls an oil regulating valve that returns oil back into compressor sump once the oil level is below a certain level (Han, 2006). This solution has the name "active solution". Normally in this configuration, each compressor needs to be equipped with one OLR which is comparatively expensive. Simple systems which link the compressor sumps via oil balancing line without OLR control have a more attractive price tag, and are called "passive solution". This solution is quite common for air conditioning applications, while for refrigeration additional considerations are to be applied. In this paper, three different passive solutions are introduced which can be applied to even tandem configurations (compressors of same capacity).

2. PASSIVE SOLUTION 1 – OIL RETURN TO COMMON SUCTION

2.1 Oil Return to Common Suction Line Solution Analysis

This solution consists of two compressors sharing one common oil separator. Oil separated in the OS is fed back to compressors' common suction line, and is then fed back to each compressor along with refrigerant gas. Figure 1 shows the schematic of this solution. To get a good oil level balance between two compressors, the oil return has to be split equally between the running compressors; the oil state could be as spray with the gas and as droplets along the length and bend of the piping. Since the oil is returning back together with the suction gas, equalizing the gas flow is critical and gas velocity in the suction line is very important.

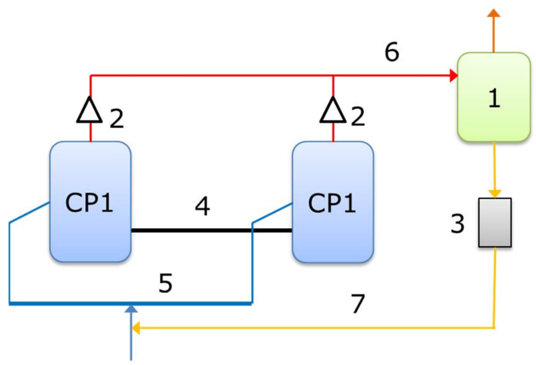

Figure 1: Schematic of oil return to common suction
1. OS; 2. NRV; 3. Oil filter; 4. OBL; 5. Suction line;
6. Discharge line; 7. Oil return line

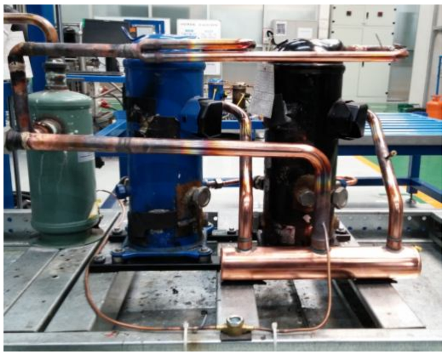

Figure 2: Oil return to common suction test

The design of a suction header and suction branch are demonstrated in Figures 3 and 4. The main suction line running from the evaporator to the compressors is connected to a suction header where the suction pressures can be equalized; the lower the gas speed in the header the better pressure equalization. The connection of suction header to individual compressors is accomplished by symmetrically arranged pipes. This is necessary to achieve a better pressure equalization for the crankcases at the compressor inlet. Figure 4 shows the cross section of the suction header, the oblique incision on suction branches are facing each other and touch the bottom of the header, which reduces the possibility of oil build-up at the bottom of the header and enhances the oil return refrigerant gas flow. The symmetric design is essential for equalizing the oil return back into each compressor. The oil balance line is installed at compressor sight glass position in order to balance the oil level when one of the compressors' oil levels is higher than the other's. The two compressors should be installed as close as possible to each other in order to keep the lines short to reduce pressure losses.

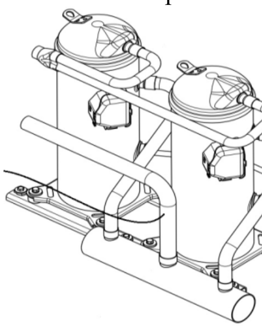

Figure 3: Even tandem pipework design

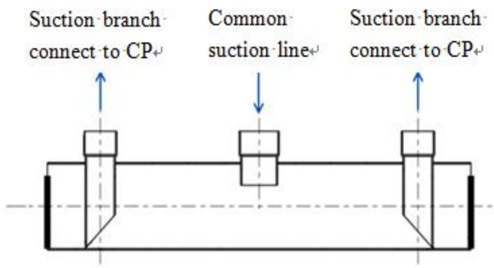

Figure 4: Cross-section of suction header

Based on above solution concept, a test is set up to verify it, see Figure 2. Two Danfoss refrigeration scroll compressors with the same model are chosen; the oil separator is selected as filter type with float ball valve. When the oil level inside the OS is higher than a certain level, the float ball valve will open and oil is fed back to compressors' common suction line. Oil balance line (OBL) is installed in sight glass position, and keeps the same center height; one more sight glass is installed on each compressor in order to observe the oil level inside the crankcase. Correct sizing of OBL is essential for oil balancing between two compressors. Different sizes of OBL are applied during the test and it is found that the smaller size OBL has less contribution to gas equalization comparing to a bigger size OBL. Finally the right size of OBL is selected for even tandem systems. Several conditions within the compressor map are selected for the validation test, and the results are shown in Table 1.

Table 1: Test result for oil return to common suction line

Condition (°C) (Tevap/Tcond)	**Running Compressor (CP)**	**Running CP oil level (oil level in SG position)**	**Standby CP oil level (oil level in SG position)**
-10/45	Single	3/4	Bottom~1/3
	Both	Full/Full	-
-10/55	Single	3/4	1/4~1/3
	Both	Full/Full	-
-25/30	Single	4/5~Full	1/4~1/3
	Both	Full/Full	-
10/30	Single	1/2	1/4~1/3
	Both	(1/2)/Full	-
-15/50	Single	3/4~Full	1/4
	Both	Full/Full	-
10/60	Single	1/3~4/5	1/3~1/2
	Both	Full/Full	-

Test results show that when a single compressor is operating, both compressors' oil level is within the sight glass, and the oil level of a running compressor is higher than of a standby compressor, this is due to lower pressure inside a running compressor. When both compressors are operating, oil level is high and the pressure balancing and consequently oil balancing are good (pressure difference is less than 2 mbar). Oil level inside the compressor's crankcase is stable, and OBL has both gas equalization and oil equalization function. For this solution, two compressors are sharing one common OS, the cost is relatively low; however, there is a strict requirement for suction pipework symmetric design and manufacturing, OBL size selection and suction header design, which is very important for the gas equalization. The OS should be efficient for both single compressor operation and two compressors operating together.

2.2 Oil Injection Position Influence

In the solution described, the oil is feeding back to common suction line from the oil separator through the float ball valve. Different oil injection positions will influence the oil mass flow distribution between two compressors. Simulation is processed with provided boundary conditions including refrigerant gas mass flow and pressure at the inlet of suction line, pressure at two suction branches outlet, oil injection mass flow and various injection positions at different heights relative to suction header (see Figure 5).

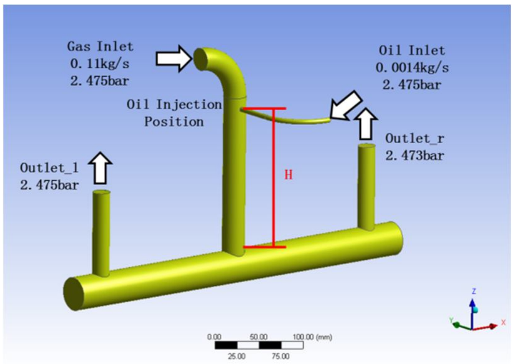

Figure 5: Oil return simulation model

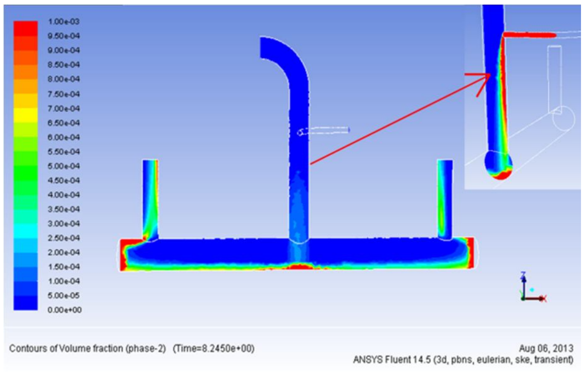

Figure 6: Oil return simulation result

Simulation is done in three different oil injection heights (H). The result shows that when oil injection position is high, the oil distribution difference is 5.79%; when oil injection is in a lower position, the oil distribution difference is much bigger – up to 15.4% as shown in Table 2.

Table 2: Simulation result for oil return to common suction line

Height (mm)	**147**	**100**	**60**
Oil Return left (mass flow kg/s)	0.000729	0.000750	0.000809
Oil Return right (mass flow kg/s)	0.000648	0.000632	0.000593
Oil Return Difference (mass flow kg/s)	0.0000811	0.000117	0.000216
Oil Distribution Difference %	5.79%	8.36%	15.4%

Based on simulation, a test equipped with even tandem system is also processed to verify the oil return position influence. Two oil injection heights – 64mm and 147mm are selected for the test as Figures 7 and 8 show.

Figure 7: Oil return position A

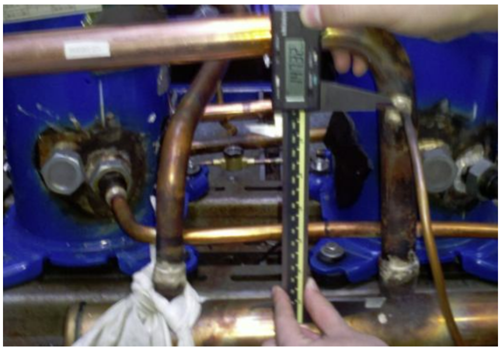

Figure 8: Oil return position B

The test results (see Table 3) show a trend similar to what simulation demonstrated.

Table 3: Test result for oil return to common suction line

Condition (°C) (Tevap/Tcond/SH/SC)	Suction Difference@ Oil return position A	Suction Difference@ Oil return position B
-10/45/11.0/0	0.54~0.76kPa	0.16~0.21kPa
-25/30/11.1/0	0.46~0.57kPa	0.36~0.44kPa

Based on the simulation and test result, a suitable oil injection position is recommended. It is suggested to keep the height of oil injection connection to common suction line on the level of at least 5 times diameter of the common suction line. It can provide a better oil distribution between two compressors.

3. OTHER PASSIVE SOLUTIONS

3.1 Passive Solution 2 – Oil Return to Compressor

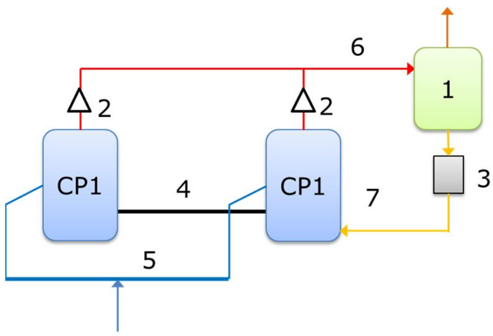

Figure 9: Schematic of oil return to compressor
1. OS; 2. NRV; 3. Oil filter; 4. OBL; 5. Suction line; 6. Discharge line; 7. Oil return line

Figure 9 shows the concept of a passive solution. The concept includes one common OS for both compressors. The oil separated in OS is returned to one compressor's crankcase and then through the OBL into another compressor's crankcase. To get a good oil level balancing between two compressors, gas equalization is significant and OBL size selection is very important as well. Same suction header design is adopted as passive solution 1 in order to achieve good gas equalization in the compressor crankcase inlet. OBL size selection is the same as passive solution 1. To verify this solution, a test is set up with two Danfoss refrigeration scroll compressors (same model) and filter type OS with float ball valve. When the oil level inside an OS is higher than a certain level, the float ball valve will open and oil is fed back to the compressors' common suction line. OBL is installed in sight glass position, and keeps the same center height; one more sight glass is installed on each compressor in order to observe the oil level inside a compressor's crankcase. Several conditions within the compressor map are selected in the test, and the result is shown in Table 4.

Table 4: Test result for oil return to compressor

Condition (°C) (Tevap/Tcond /SH/SC)	Running Compressor (CP)	Running CP oil level (oil level in SG position)	Standby CP oil level (oil level in SG position)
-10/45/11.0/0	Single	Bottom/Full	Bottom
	Both	Bottom/Full	-
-25/30/11.0/0	Single	Bottom~1/2	Bottom
	Both	Bottom/Full	-
0/50/11.0/0	Single	2/3~Full	Bottom
	Both	(1/4)/Full	-
10/30/11.0/0	Single	Bottom	Bottom
	Both	Full/Full	-

Test result shows that when a single compressor is operating, both compressors' oil level is within the sight glass, and the running compressor's oil level is not as stable as passive solution 1 due to oil feeding back to the compressor crankcase directly. When both compressors are operating, oil level is visible in both compressor's SG (oil level is above safety level in both compressors) and oil balance is acceptable although it is not as good as passive solution 1. For this solution, two compressors are sharing one common OS, the cost is relatively low; however, oil return requires an additional port on the compressor's crankcase, this leads to introduction of another compressor model for manifolding application. Obviously, this variation is unnecessary and inconvenient for compressor manufacturers. The OS should be efficient for both single compressor operation and two compressors operating together.

3.2 Passive Solution3-Individual Oil Return

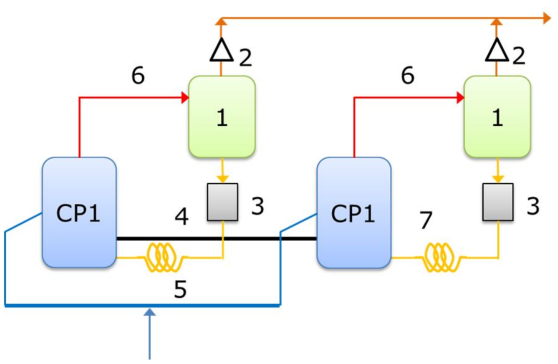

Figure 10: Schematic of individual oil return
1. OS; 2. NRV; 3. Oil filter; 4. OBL; 5. Suction line;
6. Discharge line; 7. Oil return line with a capillary tube

Figure 11: Individual oil return test

Figure 10 shows the concept of passive solution 3 – individual oil return. The concept is that each compressor has its own respective oil separator; oil separated in the oil separator is returned back to the corresponding compressor's crankcase, and the oil balance line is installed to avoid that one compressor oil level is much higher than the other if OS efficiency is different or any of the OSs is blocked. To verify this solution, a test is set up with two Danfoss refrigeration scroll compressors of same model and cyclonic type OS with capillary tube and solenoid valve to control the oil feeding to compressor, see Figure 11. OBL is installed in sight glass position, and keep same center height; one more sight glass is installed on each compressor in order to observe the oil level inside a compressor's crankcase. Several conditions within compressor map are selected in the test, and the result is shown in Table 5.

Table 5: Test result for individual oil return

Condition (°C) (Tevap/Tcond /SH/SC)	Running Compressor (CP)	Running CP oil level (oil level in SG position)	Standby CP oil level (oil level in SG position)
-10/45/11.0/0	Single	1/2	Bottom
	Both	Full/Full	-
-10/55/11.0/0	Single	1/4~3/4	Bottom
	Both	Full/Full	-
-25/30/11.0/0	Single	1/2~Full	Bottom
	Both	Full/Full	
10/30/11.0/0	Single	1/4	Bottom
	Both	Full/Full	-
10/60/11.0/0	Single	1/4	Bottom
	Both	Full/Full	-

Test result shows that when a single compressor is operating, both compressors' oil level is within the sight glass, and the running compressor's oil level is higher than that of the standby compressor due to lower pressure in the running compressor. When both compressors are operating, oil level is high in all conditions. For this solution, each compressor has its own OS; the accessories are more than passive solution 1 and 2. However, the design requirement for symmetric suction pipework is not as strict as in solution 1 since oil return relies on OS efficiency, not on suction gas flow. Also, the efficiency of OS only needs to meet single compressor running condition.

4. VIBRATION SIMULATION

The qualification process of manifolding solutions includes vibration test, designed to identify resonant frequencies of the structure and improve the design of the piping or main structure accordingly. Since the piping design is critical for successful oil balancing, it is a better approach to perform a preliminary vibration check at the stage of design. A model for FEA analysis was made based on the piping design (Figure 12) while experimental modal analysis was performed on a powered off tandem unit connected to the test bench by designed piping. The results of modal analysis were used for model optimization. Comparison results are given in Table 6.

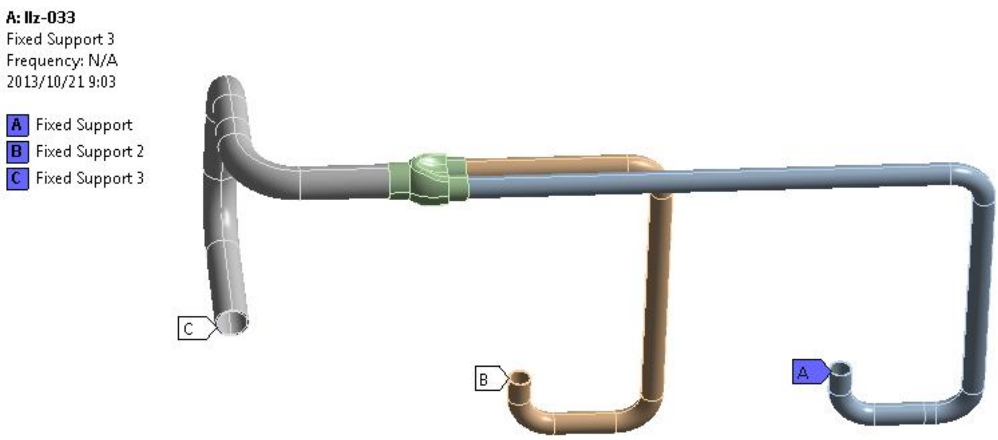

Figure 12: discharge pipe model for the first round FEA

Table 6: Test result for the first round of study

Natural Frequencies, Hz		Difference		Mode match
Experiment	Calculations	Absolute	Relative	
48.2	49.3	1.1	2%	Yes
87.7	83.7	-4.0	5%	Yes
93.1	91.8	1.3	1%	Yes
129.9	129.8	-0.1	0%	Yes
160.4	153.1	-7.3	5%	Yes
192.6	188.3	-4.3	2%	Yes

The results of optimization were good as all the natural frequencies with correct modes were matching the experiment results within 5% error.

For the second round, the discharge pipe configuration was changed and another set of tests and calculations were launched (Figure 13). The FEA calculation had been performed prior to the experiment, therefore the model and boundary conditions were kept the same as for the first round. Results are given in Table 7.

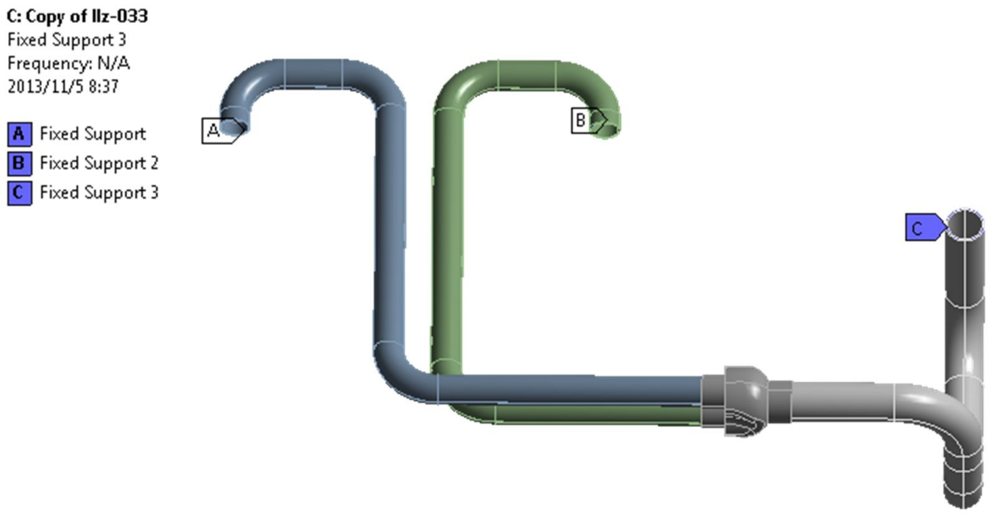

Figure 13: discharge pipe model for the second round FEA

Table 7: Test result for the second round of study

Natural Frequencies, Hz		Difference		Mode match
Experiment	Calculations	Absolute	Relative	
57.4	58.7	1.3	2%	Yes
94.1	100.5	6.4	7%	Yes
113.7	134.4	20.7	18%	Yes
140.2	156.5	16.3	12%	Yes
-	172.1	-	-	-

The results of calculation are acceptable within 0 – 100Hz range, while having a significant shift in a higher frequency range. Although the modes were generally described correctly, there was still a missing mode in experiment.

The third round of the study included significantly changed piping design (Figure 14). As in the previous round, the FEA calculation was done before the experiment. The results of comparison are shown in Table 8.

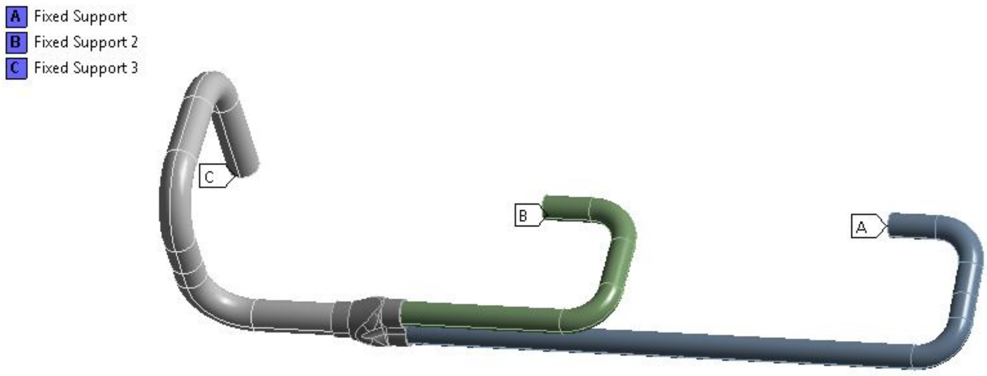

Figure 14: discharge pipe model for the third round FEA

Table 8: Test result for the second round of study

Natural Frequencies, Hz		Difference		Mode match
Experiment	Calculations	Absolute	Relative	
107.8	125.0	17.2	16%	Yes
136.8	156.5	19.7	14%	Yes
160.7	185.5	24.8	15%	Yes

The results of calculation and experiments deliver information that there are no natural frequencies below 100Hz, and the modes after 100Hz were described correctly. A trend was noticed that with increased rigidity of the piping, calculation results were shifting to higher values than experimental values. The reason may be that with increased rigidity of the piping it starts influencing the main structure (CPs and OS).
Combining vibration test results with operating conditions, no resonance frequency was found between 45-65Hz, and all the maximum vibration displacements are below limitation. The study showed a good process of piping design for manifolding compressors.

5. CONCLUSIONS

Above analysis shows that all of the three different passive solutions can ensure oil return and balance for even tandem systems of refrigeration scrolls, while each solution has its own advantages and disadvantages. The solution of oil return back to the compressor crankcase has limitations on the compressor structure – it requires an oil return tube connection on the compressor shell. The solution of individual oil return needs two OSs, meaning higher cost. The solution of oil return back to the common suction line is recommended here due to the low cost and no limitation on the compressor structure. For this solution, it is suggested that the height of oil injection position to header is no less than 5 times the diameter of the common suction line in order to get equal oil distribution; gas velocity inside the suction header is no more than 4m/s in order to obtain a good gas equalization between two compressors. The comparison table 9 shows the pros and cons of each solution.

As a part of the current work, the study of optimized design process for manifolding solution was carried out. Modal analysis through FEA calculations shows good convergence with experiment results for the case of a flexible structure while natural frequencies of more rigid structures start shifting towards higher values although the modes are described correctly. It indicates that there is an influence from the main (heavy) structure on the piping, which was considered negligible in the first round of the study.

Table 9: Comparison of three passive solutions

Items	Solution 1 – oil return to common suction	Solution 2 – oil return to compressor	Solution 3 – individual oil return
Long/short circuit	Long	Long	Long
Reliability	Good	Good	Good
Cost	Low	Low	High
Standard Compressor	Yes	No	Yes
Application	Even tandem	Even tandem	Even, uneven & multiple compressors more than two

NOMENCLATURE

CP	compressor	(–)
FEA	finite element analysis	(–)
NRV	non return valve	(–)
OBL	oil balancing line	(–)
OLR	oil level regulator	(–)
OS	oil separator	(–)
SC	subcooling	(K)
SG	sight glass	(–)
SH	superheat	(K)
Tcond	condensing temperature	(°C)
Tevap	evaporating temperature	(°C)

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